# HYBRID TECHNIQUES TO ENHANCE SOLAR THERMAL: THE WAY FORWARD

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## ABSTRACT

Solar is one of the pillars for clean and environment friendly energy. The drawback of the solar is the interruption during the night and cloudy and rainy weather. This paper presents the author's experience on enhancing the solar thermal systems by integration techniques with either other energy resources or thermal energy storages (TES). The present works includes the hybrid solar drying through integration with thermal backup unit. The experimental results on hybrid drying showed enhancement of 64.1% for Empty Fruit Bunch, and 61.1% for chili pepper, compared with open solar mode drying. Secondly, solar water heating was proved to be sufficient to supply hot water during the day and night time by integration with TES. The experimented system was able to maintain the water hot up to the next morning. On large scale and industrial application, experimental results on modified inclined solar chimney had shown enhancement via integration with wasted flue gas. By this technique, the system was developed to operate 24 hours a day. The efficiency was enhanced by 100% in case of hybrid operation compared with solar mode operation. The research results are demonstrating that the integration techniques can contribute effectively in enhancing the performance of the thermal solar systems.
*Keywords: Energy sustainability, hybrid solar dryer, PCM, solar chimney, solar energy, solar water heater, sustainability, TES, waste to energy.*

## 1 INTRODUCTION

Solar energy finds its importance by moving from domestic to industrial and large-scale power generation effectively. The range of small-scale solar applications include hot water systems, solar distillation of sea and brackish water, water pumping, drying of agricultural products, space heating and cooling, day lighting, solar refrigeration and building integrated photovoltaic systems. Solar energy becomes one of the most promising resources for power generation in a large scale. Electric power can be generated by direct conversion of sunlight into electricity using photovoltaic or indirect conversion using solar thermal systems like the parabolic trough systems, central receiver systems, dish-Stirling engine systems and solar chimney power plant (SCPP). But, all those applications are facing setback represented in the non-continuous availability of the solar all around the day. Adding the fact that it is transient over the day time, and it is highly influenced by the cloudy and rainy weathers, solar thermal systems become questionable for industrial applications. This setback encouraged researchers to create ideas and technologies to reduce the interruption effect of the solar energy on the system's performance and plant's productivity whether in small-scale or large-scale applications. Among the practical techniques used to enhance the solar thermal systems are the integration with thermal energy storages (TES), while integration with thermal back up units (TBU) as auxiliary resources are studied mainly in the topic of solar drying and water heating.

This paper presents the efforts made by the solar energy research group in Universiti Teknologi PETRONAS (UTP) to create and investigate the integration techniques to enhance the performance of thermal solar systems. Developed solutions for over the day around; of solar drying, solar heating and power generation are presented and discussed. At the end of the article, the promising DESERTEC project is presented as an example of global trend towards solar thermal integrated power generation approaches.


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## 2 HYBRID SOLAR DRYING

Some attempts have been reported to enhance the drying performance through integration of solar energy with TES or thermal back up. Madhlopa and Ngwalo [1] studied solar dryer with biomass backup heaters, which were made of brick and consisted of rock pebbles acting as TES. Thanaraj *et al*. [2], Prasad and Vijay [3], Prasad *et al*. [4], Tarigan and Tekasakul [5], and Bena and Fuller [6] used bricks, clay and cement to construct a furnace, which consisted of heat exchanger to a solar dryer. Mastekbayeva *et al*. [7] reported a solar hybrid tunnel dryer incorporated within a biomass stove-heat exchanger, which consists of a cross-flow shell and tube heat exchanger. Serafica and del Mundo [8] and Bhattacharya *et al*. [9] investigated a biomass gasifier stove design as a backup heater to the hybrid solar dryer for fish, fruits and vegetables. The biomass gasifier consists of shell and fin heat exchanger configuration, and the heat delivery and combustion rate could be controlled by a butterfly valve at the air inlet.

Kanmogne *et al*. [10] studied a hybrid solar/wood prototype of dryer for the agro-alimentary drying of the cocoa, in particular. The drier is composed of 3 m × 2 m × 1.2 m room, two hearths consist of stainless sheet steel of parallel epipedic, and two galvanized steel tubes with diameter 135 mm across the room constitute the heat exchanger. The roof of the drier is made out of plexiglass to optimize solar energy in the drying room. They claimed that it is possible to dry 100 kg of fresh cocoa in 50 h by using energy coming from wood and 35 kg in 40 h by using solar energy.

Among the biomass fuel materials that have been used as fuels in the TBU are coconut shells [8]; woodchips [9,1]; charcoal [4]; paddy husk [5]; fuel wood [3,5,6,10]; and briquetted rice husk [7].

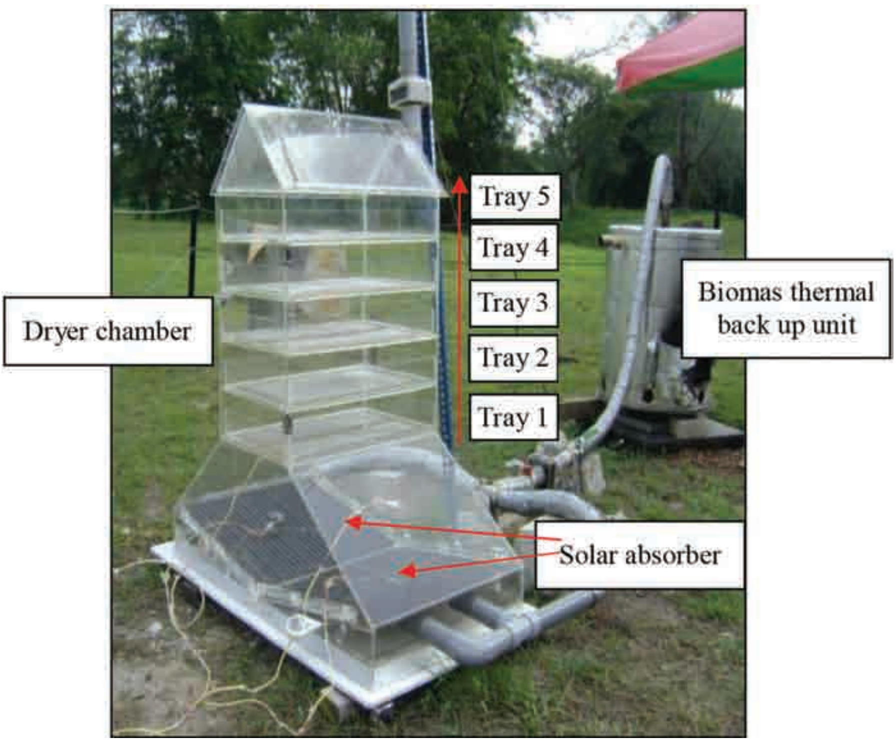


Figure 1: The experimental set up of a hybrid solar dryer in UTP.

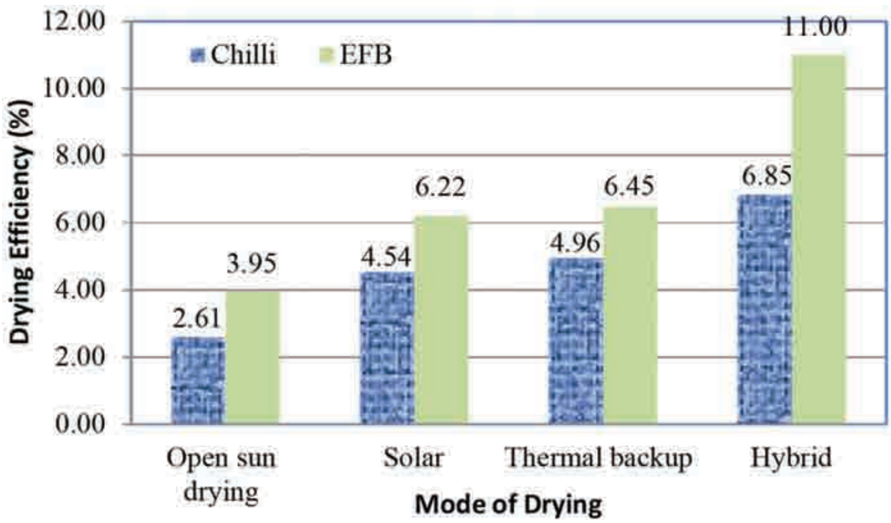


Figure 2: Drying efficiency of chili and EFB at various drying modes.

A hybrid solar dryer was designed, fabricated and evaluated to dry various types of materials. Chili was selected as the food and EFB as the biomass. The hybrid drying apparatus consisted of a solar dryer integrated with specially designed and fabricated biomass burner. Gas-to-gas heat exchanger as TBU. The apparatus is shown in Fig. 1.

The results of drying efficiency of EFB and chili under different operational modes are shown in Fig. 2. The lowest efficiencies for drying were found in open sun drying where the drying process took a long time.

It is noted that the highest efficiencies were obtained in the hybrid drying mode. The EFB drying efficiency was enhanced by 64.0% and the chili drying was enhanced by 61.0%. Details of the TBU are available in Yunus *et al*. [11]. Details of the drying of the EFB, including the measurements methodology and evaluation, are reported by Yunus and Al-Kayiem [12].

## 3 HYBRID SOLAR WATER HEATING

Electrical heating elements to replace solar energy at night are the common practice for continued hot working fluid supply. The working fluid may be air, water or oil. However, the new trend in compensation for the interruption of the solar energy is the integration of the solar absorber with TES. Though the basic idea on solar energy storage has not changed, many innovative solar collectors have been proposed and tested. Reis *et al*. [13] used water-filled barrels as solar collectors. Reddy *et al*. [14] came out with a sand mix concrete absorber solar collector buried in the ground. Hamdan [15] designed a metallic box solar collector. de Beijer *et al*. [16] developed a system that incorporates two cylindrical tubes; an outer tube was coated with selective surface to act as a absorber and the inner tube acts as storage. Goetzberger and Rommel [17] investigated the performance characteristics of solar transparent honeycomb-insulated passive hot water system using both water and ground as collectors. Solar-integrated collector storage for water heating system is simply a combination of collection and storage in a single unit. The elimination of a separate storage tank and the collector from the conventional solar heater makes it cost effective. However, it may have a relatively low efficiency as mentioned by Shmidt *et al*. [18].

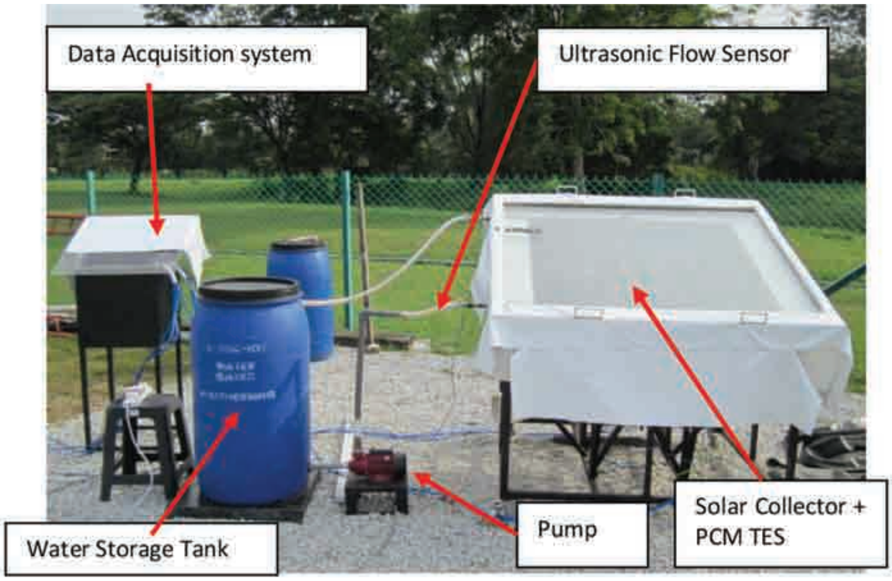


Figure 3: Experimental set up of an integrated solar-PCM TES water heater in UTP.

A solar collector integrated with a PCM-TES was designed, fabricated and evaluated at various operational modes at UTP – Malaysia, as shown in Fig. 3.

The averaged results of 5 days measurements at 10° inclination are presented in Fig. 4. The PCM started to store the energy at 9.00 AM and solidify at 6.00 PM. All the temperatures reached equilibrium at 12 midnight. Five hours extensión period of wáter heated by PCM from 7.00 PM to 12 midnight were achieved, and the water temperature obtained for domestic use was around 40°C.

## 4 HYBRID SOLAR-FLUE CHIMNEY POWER PLANT

Solar-thermal technologies are feasible alternatives to traditional energy sources; e.g. oil, coal and nuclear. Solar-thermal systems are not only faster and easier to implement but they are also exceptionally environmental friendly and produce power with zero $CO_2$ emission. Building more solar-thermal power plants may eliminate the dependency on coal, oil and nuclear energy and thereby advance the reduction of greenhouse effect and global warming.

In 1981, the German structural engineering company, Schlaich Bergermann and Partners (SBP) proposed, designed, built and tested a SCPP in Manzanares, Spain. The plant has a collector diameter of 240 m and a chimney of 196-m high with 10-m diameter. It is the largest constructed SCPP to date designed to produce 50 kW electricity [19]. Considering the experimental results from the SCPP in Manzanares and different research models developed so far, SCPP total efficiency is still below 0.2% and depends largely on the chimney height and the collector area [20]. Many approaches have been suggested to enhance the system performance and were summarized in a review paper by Chikere *et al*. [21].

In 1997, Kreetz [22] introduced the concept of water-filled tubes under the collector roof for thermal energy storage. His simulation results showed more stability over continuous 24-h operation of the solar chimney power plant with wáter-filled bags (water tubes) inside the collector using varying depth of the tubes. The results are shown in Fig. 5.

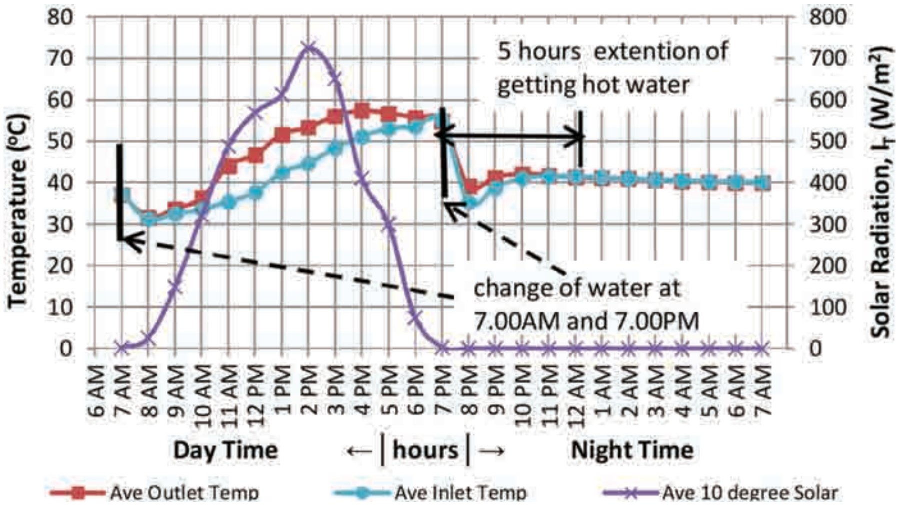


Figure 4: Experimental results of an integrated solar-TES using paraffin wax as PCM.

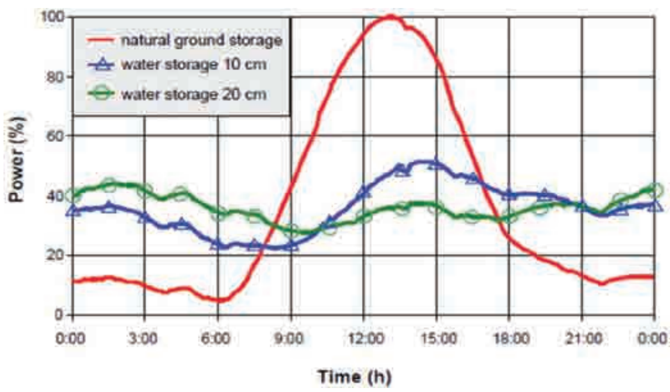


Figure 5: Continuous operation of SCPP using water-filled bags [22].

Bernardes [23] investigated the possibility of using water-filled tubes on the collector floor as heat storage device and found that its implementation smoothed out the daily fluctuation of power output and, hence, increased the power output after sunset. Hussain [24] proposed hybrid geothermal/SCPP and hybrid geothermal/PV/SCPP for prospective SCPP in the south region of Libya. Akbarzadeh *et al*. [25] examined the potential benefit of combining a chimney with a salinity gradient solar pond for the production of power in salt affected areas.

Elementary experimental measurements on an inclined solar chimney model integrated with flue gas were reported by Al-Kayiem *et al*. [26]. Then, the same system was simulated and the simulation results were validated through comparison with the measurement results as reported by Al-Kayiem *et al*. [27]. The experimental and simulation boundary conditions are shown in Fig. 6.

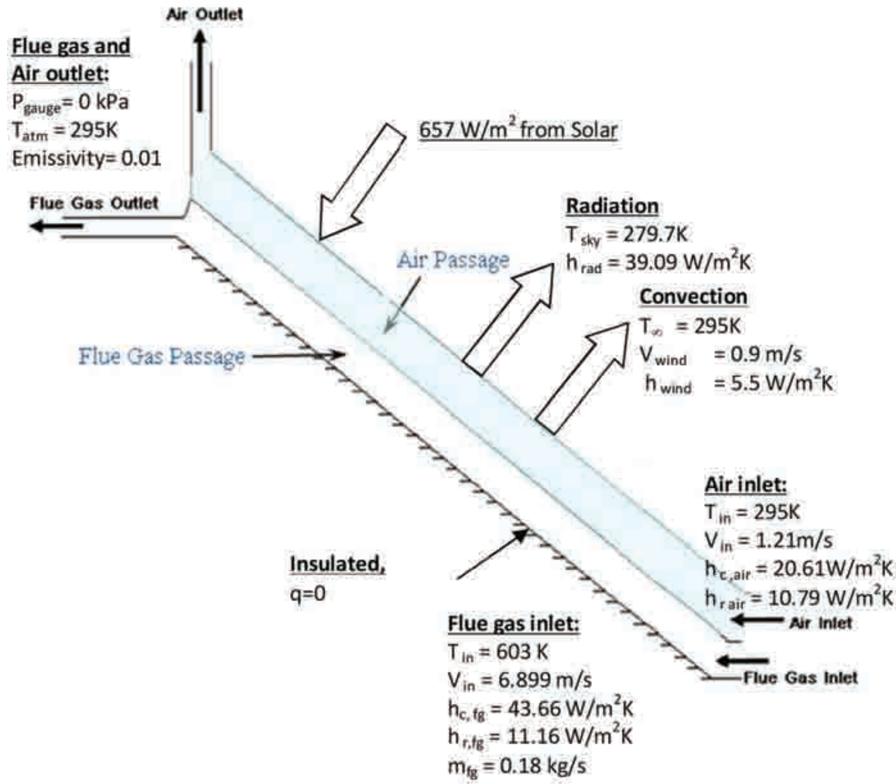


Figure 6: The boundary conditions of the model.

Table 1: Validation of the simulation criteria by comparison with experimental results.

| Boundary conditions | $T_{flue}$ in (K) | Results of air velocity at exit (m/s) | | Error (%) |
|---|---|---|---|---|
| | | Experiment (K) | Simulation | |
| Flue mass flow rate = 0.18 kg/s | 603 | 2.17 | 2.36 | 8.7 |
| | 843 | 4.41 | 4.95 | 12.2 |
| | 983 | 5.24 | 5.86 | 11.8 |

The predicted results from the simulation have been compared with the corresponding experimental results. The cases considered are with three different flue inlet temperatures, as shown in Table 1.

The mean percentage of absolute error in the predicted velocity is around 10%. The predicted values from the simulation are higher than the experimental measurement results. This is due to the losses that take place at the back and from the sides of the fluid flow channels. The other reason is the estimation of the convection heat transfer, which was carried out separately assuming constant properties of fluids and materials. However, this range of error in the simulation results of convection heat transfer is acceptable and is justified enough to study the effect of the other parameters, taking into consideration that this is a design project rather than investigation of the fluid and heat behavior in the system.

Extended work was carried out on modified double-inclined solar-flue gas chimney PP (S-FGCPP), as suggested by Chikere *et al*. [21]; this was designed, fabricated and tested experimentally as shown in Fig. 7.

The system comprises rectangular air solar heater integrated from underneath with hot flue gas channel. Flue is supplied from a biomass burner. A nozzle conduit is directing the warm air at the exit of the air heater to a circular chimney. During the day, the heat source is the solar, while during the night, the heat source is gained from flue gases.

The measurement results show considerable enhancement in the system after integration with flue gas. By recovering the wasted heat from flue to the air in the chimney, it is found that the system can operate all around the day with more stable power output. Comparison of the efficiency results of the solar and hybrid modes is shown in Fig. 8.

Furthermore, simulation has been carried out, by adopting the same design and operating conditions of Manzanares SCPP, to determine the applicability of the approach of S-FGCPP on large prototype scale. Two simulations have been carried out using ANSYS software. One was to simulate the system under solar mode, whereas the second was to simulate the hybrid

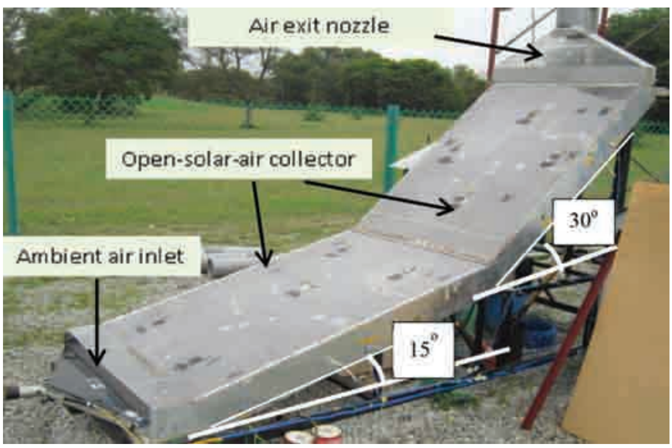


Figure 7: The experimental model of the hybrid S-FGCPP in UTP.

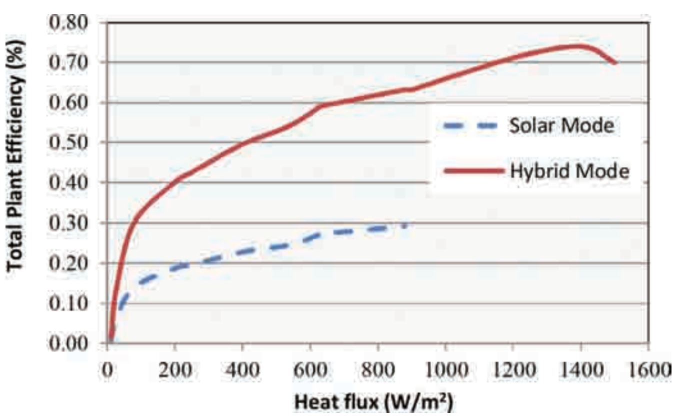


Figure 8: Total plant efficiency of solar mode and hybrid mode.

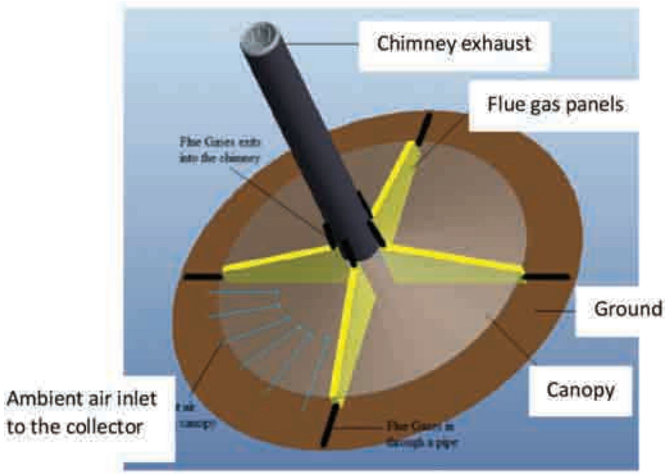


Figure 9: Simulated hybrid solar chimney PP integrated with flue gases.

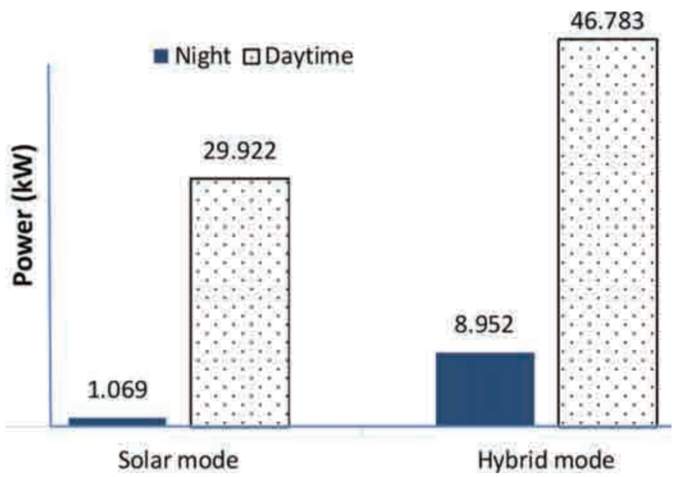


Figure 10: Comparison of SCPP plant efficiency for solar and hybrid modes.

mode. The model of the simulated system is shown in Fig. 9. The hybrid mode is representing solar plus waste to energy of flue gas exhausted from thermal power plant.

The simulation results proved that the plant is capable of delivering power during the night. Also, daytime power generation is increased as both solar and flue are contributing in supplying thermal energy to the air in the collector. This also caused the overall efficiency of the plant to increase. When assuming 1000 W/m$^2$ solar intensity, the simulation results of the two operation modes are presented in Fig. 10. For more details on the influence of the temperature, velocity and power, a reader can refer to Azeemuddin *et al*. [28, 29].

## 5 MEGA HYBRID POWER PROJECTS

Renewable energies have gained larger attention after the nuclear crises in Japan after the tsunami. Energy producers, researchers and investor started to debate about mega scales of hybrid energy production. Many promising projects that contribute to the solution of the


Figure 11: Sketch of possible infrastructure for a sustainable supply of power to Europe, the Middle East and North Africa (EU-MENA) (Source: DESERTEC Foundation, www. desertec. org).

electric power are proposed; as examples are the Sahara – EU solar project (DESERTEC) [30]. By 2050, according to its backers, DESERTEC, a network of solar plants and other renewable sources scattered across North Africa and the Middle East, could generate more than 125 GW of power that could be used locally or delivered to Europe through high-voltage direct-current cables beneath the Mediterranean Sea (Fig. 11).

This mega scale project integrates the thermal power plants, which are existing in Europe with the produced power by solar, wind, geothermal and biomass. It will extend from the Gulf to Saudi Arabia and Iraq to Europe through Turkey; and from North and the west coast of Africa through Spain, France, Greece and Italy. The project connection is extending to the North Sea up to the Iceland.

## 6 CONCLUSION

Analysis of proposed and investigated approaches for enabling the continuous day and night operation of solar thermal systems is represented. The investigations involved hybrid solar applications on drying, water heating and power generation. The partial availability of solar energy in the day and the transient nature of solar energy are compensated by integration with other clean resources. With the hybrid proposed technologies, the performance of the solar thermal systems is enhanced by bringing the systems to operate continuously over the 24 h per day with higher efficiency.

The conclusions that could be drawn are:

- The solar drying has been improved by integration with thermal back up such as biomass burner.
- Domestic water heating was improved and overnight hot water production was attained via integrating the solar absorber with PCM TES.
- In the power production by SCPP, the performance can be improved by integration with waste flue gases. Results are showing higher stability in the power production, higher efficiency and continuous 24 h per day operation.
- The world realized the importance of the hybrid technologies to enhance the performance of each individual source of energy, whether it is conventional or renewable type. Mega hybrid projects are proposed.

The results are encouraging and it is recommended to further investigate various integrations and back up technologies to enhance the performance of the solar thermal systems.

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